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AN OBJECTIVE MEASURE OF DISCOMFORT GLARE

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ABSTRACT

Although it is relatively easy to perceive and report the sensation of discomfort caused by the presence of an offending light source of high luminance, no one has yet found a reliable objective correlate correlate of discomfort glare.

In order to find an objectively measured correlate of discomfort glare, we have examined electrical activity associated with the two major facial muscles that surround the eye, viz. the *orbicularis oculi* and the *corrugator supercilii*. We have made electromyographic (EMG) recordings using small silver/silver chloride electrodes applied to the skin above the muscles and measured electrical potentials while lighting glare conditions have been changed. Intensities were varied over a range of glare luminance determined by a separate procedure according to subjective ratings. For this subjective method, subjects indicated the level of discomfort by marking a Visual Analogue Scale (VAS) punctuated with four descriptions of discomfort level: perceptible, annoying, disturbing, and intolerable. We have determined that the VAS is much more reliable with much less variability than the previously used border Between Comfort and Discomfort (BCD) method.

For 19 subjects, discomfort glare was assessed under three conditions: 2 deg. diameter glare source with low room illumination, 2 deg. glare source with medium room illumination, and 1 deg. glare source with medium room

illumination. The glare source was a projector beam, 11 deg. to the right of a fixation target on a video monitor. Six different glare luminance levels were presented for 2 second periods. Each glare level was presented six times in a randomized order giving 36 presentations.

EMG responses were subjected to Fourier analysis and the power frequency spectrum was determined with appropriate digital filtering used to eliminate power line artifacts. Blinking causes an artifact whose power spectrum is markedly different and can be determined independently of the glare source. The integrated power spectrum of the EMG activity during exposure to the glare source was compared to the same integral prior to exposure to obtain a quantitative measure of glare induced activity. For each of the 19 subjects and a variety of glare conditions, the objective measure and the VAS have been plotted as a function of glare luminance. For individual subjects we found increasing objective measure and increasing subjective discomfort with increased glare luminance. We conclude that the EMG technique is a vlaid objective means of assessing discomfort glare.

INTRODUCTION

More than 60 years have transpired since Luckiesh and Holladay[1], and independently, Stiles[2] first proposed that illumination conditions present two different types of glare effects. These attributes are referred to as disability glare and discomfort glare. In the first case, the glare condition produces veiling luminance which reduces the contrast of the task with a resultant decrease in visual performance. Detailed quantitative studies have evaluated disability glare (see e.g. Vos[3]) and the phenomena appears reasonably well understood. The same cannot be said of discomfort glare which is a measure of negative subjective reaction to the presence of a glare condition. Although there are extensive studies based on measures of subjective response, no clearly identifiable objective correlate has been established. Hopkinson[4] and later Fry and coworkers[5], have claimed that the behavior of the small random uncontrolled oscillation of the pupil aperture (hippus) is affected by the presence of discomfort glare. Recent attempts to verify possible changes in the power spectrum of hippus when discomfort and no discomfort occurred but average pupil size was the same showed no differences[6] even when the reported discomfort was at the near intolerable level. Thus, although it is relatively easy to perceive the sensation and elicit a negative response to the presence of discomfort glare, the absence of a reliable objective correlate remains both a puzzle for vision science and a barrier to rational optimization of the quality and efficiency of lighting design. Modern design trends towards smaller and higher luminance lighting systems coupled with a desire to increase the use of daylight provides a further impetus for achieving a better understanding of the nature of discomfort glare.

It has been known for some time through the use of electromyographic (EMG) techniques that the frontalis muscle region of the forehead have increased activity in response to conditions of increased stress or excitement (e.g., Woodworth and Schlosberg[7], Balshan[8], Malmo[9]). Furthermore, EMG responses in facial muscles have demonstrated strong evidence for correlations between EMG activity and psychological state such as sadness, anger, disgust, fear and happiness (Ekman and Friesen[10]). More recently both cognitive and affective state which is not normally observable by inspection of facial expression when studied on video tapes have shown detectable differences in EMG responses (e.g., Cacioppo and Petty[11], Ekman[12,13], Cacioppo et. al.,[14]). Furthermore, Cacioppo[15] has reported that in his study of affective state and EMG responses that lighting levels during experimentation should not be excessive.

We have studied the EMG activity of facial muscles in the vicinity of the eye as a possible measure of efferent pathway response to the presence of discomfort glare sensation. The hypothesis is that the discomfort sensation gives rise to an incipient aversion response to the glare in the form of a subtle involuntary contraction of the muscles around the eyes. This response would manifest as heightened EMG activity in the orbicularis oculi (which is the principal muscle responsible for closing the eye) or other nearby muscles such as the corrugator supercilii. Our preliminary experiments demonstrated that the presence of a small, bright and uncomfortable glare source produced demonstrable changes in the EMG. Figure 1 shows an EMG recording from a young subject. The glare source is exposed half way through the recording and produces a clear increase in EMG activity.

In preliminary studies we experimented with electrode placement, analysis techniques, and investigated some possible artifacts. Electrical activity of the orbicularis oculi was recorded, using two surface electrodes positioned on the brow. A third electrode served as a ground. Other locations, including the earlobe, gave equivalent results. These are connected to a Grass amplifier which in turn is interfaced to a PC via a A/D board. EMG activity was typically recorded for a five second period, sampled at 1000 Hz. A small intense glare source, whose exposure was electronically controlled by a shutter, was employed for all preliminary studies (for additional details see test conditions below).

Preliminary Studies

Analysis Methods

The EMG has been used in other fields of ergonomics, notably in posture evaluation (see Corlett[16]). In clinical EMG studies, it is often the quality of the signal that is of interest. In human factors research, however, it is usually the quantity of the response which is important. There are three major methods of analysis of the quantity of the EMG response:

- Integrated EMG (IEMG) Analysis
- Fourier Analysis
- Amplitude Probability Distribution Function (APDF) Analysis

The IEMG gives a measure of the power of the EMG by summing the rectified signal over a period of time. This can be accumulated to give a single value representative of the muscular activity. Alternatively, the signal can be integrated until a certain total value has been reached and starting the addition again. The visual record will show a series of triangular waves, with equal peaks but spaced more closely when the EMG signal was greater. The number of peaks per unit time provides values representative of the muscular activity.

Fourier analysis is a procedure which breaks down the waveform into its sinusoidal temporal frequency components. Typically short EMG samples are taken, analyzed and displayed as a frequency power spectrum. The advantage of this analysis is that energy at specific frequencies can be digital filtered. This particularly important if 60 Hz power line artifacts are present in the EMG or if a range of certain frequencies are contributing to a confounding or artifactual response (see discussion of blinks below).

Jonsson[17] and Hagberg[18] have demonstrated the utility of APDF analysis, which analyzes the EMG in terms of the amplitudes present in the signal. EMG samples are taken and amplitudes of all the peaks counted and grouped. These may be plotted as an amplitude spectrum or a cumulative amplitude distribution function.

We experimented with a variety of analysis techniques including Fourier analysis and IEMG. We chose to adopt Fourier analysis since it gave the cleanest results and facilitates frequency-specific filtering. The latter property was particularly important given the potential contamination of the results by power line artifacts. Power line artifacts appear in the Fourier spectrum as spikes at 60 Hz and harmonics. Fourier analysis permits the use of post-hoc digital filtering to eliminate the contamination at these frequencies. We found that integrating the derived FFT provided a reliable index of EMG activity. These integrals obtained with and without a glare source could be compared to give us an index of the discomfort (see Results and Analysis section later).

Blinks

We considered the possibility that the observed changes in EMG activity were merely due to blinking. This also raised the question as to whether the periodic blinking by subjects would contaminate our results. Inspection of EMG activity revealed that blinks were easily identifiable as large, slow changes in potential lasting some 250 msec (see Fig. 2). While blinks show a completely different waveform to the increase in activity induced by the glare source (see Fig. 2), we wanted to quantify their influence on the Fourier spectrum. We therefore collected EMG samples under constant experimental conditions, both with and without the glare source, and divided them into those which contained blinks and those which contained no blinks. Fourier analysis was performed on both subsets and the results for one comparison are displayed in Figure 3. The analysis revealed that the only substantial difference between the two samples occurs at low frequencies (<10 Hz). This is consistent with the waveform in Figure 2. In all subsequent experiments we eliminated all frequencies below 10 Hz from our analysis of EMG activity, thereby, removing the influence of blinks.

Onset/Offset Artifacts

We also considered whether the onset of the glare source produced transients in the EMG which were responsible for our encouraging preliminary results. We compared two protocols in which a small intense glare source was exposed for five seconds (see Test Conditions below). In one there was a gradual onset with the glare source luminance increased gradually over the first three seconds and then was kept constant for the subsequent two seconds. The second was a rapid onset condition, in which the maximum luminance was reached immediately and maintained for five seconds. For the rapid onset condition, there was little variation in EMG amplitude for the duration of the recording. For the gradual onset condition, the EMG increased in amplitude for the first three seconds and then stabilized. Between the protocols there was no difference for the final two seconds of glare exposure. We concluded that a rapid onset of the glare source does not produce any significant artifacts and that it is acceptable to use a shutter to control exposure of the glare source.

Electrode Placement

We have experimented with a number of electrode placements, including cheek, canthus, lid, forehead and at various locations along the brow. We found that positioning the electrodes along the inner brow gave the most reliable, robust recordings as well as being relatively unaffected by between-subject variations in facial musculature.

Subject Posture

We had observed that periods of a few minutes on a chin rest resulted in increases in EMG amplitude even without the presence of a glare source. This was not unexpected since the EMG has been used in the evaluation of postural comfort. Placing a subject in a comfortable chair and avoiding the chin rest effectively eliminates such contaminants.

Eye Movements

A further possible contaminant was changes in EMG activity due to eye movements. We compared EMG activity in the absence of any glare source under two conditions. In the first, the subject steadily fixated a target on a monitor. In the second, the subject alternately fixated two targets separated by 15 deg.rees on the screen. This required relatively large saccadic eye movements. We observed no difference in EMG activity between these two conditions. In particular, there were no transient changes in the EMG associated with the saccades.

Following these preliminary investigations, we embarked on a study of twenty subjects to compare the assessment of discomfort glare using our new objective technique with an established subjective methodology.

SUBJECTS AND METHODS

Subjects

Twenty subjects aged between 18 and 36 years (mean = 25.2 ± 3.7) each participated in one session lasting approximately 90 minutes. Informed consent was obtained from all subjects after explanation of the purpose of the study. The volunteer subjects were students and were paid for their participation. Eight of the subjects were male, thirteen were Caucasian, five were Asian, and two were of mixed race. Seven subjects wore spectacles and seven wore contact lenses.

Electrode Placement and Application

At the beginning of the session, three silver/silver chloride surface electrodes, 3 mm in diameter, were placed on the subject (as shown in Fig. 4). Two were positioned just above the eyebrow, the first vertical from the inner canthus and the second was 10 mm to the temporal side of the first. The use of two closely lying electrodes allows for a significant noise reduction due to distal muscular activity by using the common mode rejection technique. In this case, the difference signal between the paired electrodes that are mounted on the facial skin at the orbicularis oculi, is recorded and amplified by the signal processing system. Distal signals are likely to be common to both electrodes and would be eliminated by the differencing procedure.

This common mode rejection technique is generally recommended by EMG researchers (Fridlund & Cacioppo[19]). The third electrode served as a ground and was placed high on the subject's forehead. Prior to application, the skin was cleaned with alcohol and skin resistance lowered by light rubbing with a mildly abrasive skin preparation lotion (Omni-Prep). Annular self-adhesive electrode washers (In Vivo Metric E401) were then placed on the appropriate skin locations. The electrodes were then fixed to the skin with a conductive electrode paste (Ten 20). The electrodes were connected to a Grass amplifier. The amplified signal was then relayed to a IBM 386 computer via a analog to digital converter (Data Translation). Data was sampled at 1000 Hz.

Testing Conditions

Subjects sat in a comfortable chair and fixated a monitor at 1 meter (8 x 10 deg., luminance, 69 cdm^{-2}) on which a large symbol was displayed (see Fig. 5). The glare source was provided by a 300 watt tungsten halogen projector lamp with its beam positioned 11 degrees to the right of fixation and directed at the subject. Exposure to the source was controlled by a electronic shutter placed in front of the projector lens. The size of the glare source could be varied by placing a 1 deg. or 2 deg. aperture in the plane of the shutter. The luminance of the glare source (maximum = 6.9 log cdm^{-2}) was modified by neutral density filters in 35 mm slide mounts and stored in a standard carousel. The shutter and carousel were controlled by a second computer.

Discomfort glare was assessed under three conditions in a randomized order:

1. Moderate room illumination (wall luminance = 12 cdm^{-2}) and a 2 deg. glare source.
2. Low room illumination (wall luminance = 0.5 cdm^{-2}) and a 2 deg. glare source.
3. Moderate room illumination and a 1 deg. glare source.

The results of previous workers[20], led us to believe that these conditions should produce small but measurable variations in discomfort.

For each of the three experimental conditions, discomfort was assessed using both objective and subjective methods in a single experimental session lasting approximately one hour. The order was randomized with respect to both experimental condition and measurement method. For both methods, each experimental run consisted of 36 trials. Each subject was exposed to six different glare luminance levels, ranging from 4.4 to 6.9 log cdm^{-2} in equal steps. Each luminance level was presented six times in a randomized order. Subjects were instructed to look at the center of the monitor and not look at the glare source.

Subjective Method

For the subjective assessment of discomfort glare, we used a visual analog scale an approach similar to that employed by several workers (e.g., de Boer[21], Sivak et al., [22]). This technique has been found to be more reliable than the method of adjustment and 2-alternative force choice testing (Jacobs et al.,[23]). The visual analog scale comprised a 100 mm horizontal line with a series of demarcations. These marks were positioned to signify the borders between perceptible, annoying, disturbing and intolerable discomfort. Subjects were provided with written descriptors of each of these sensations at the beginning of the experimental session (see Appendix) and the key words were displayed at the top of all recording sheets. Subjects were instructed to place a line or check mark on the scale to indicate their perceived level of discomfort. For example, a source which the subject felt was annoying but did not approach disturbing discomfort might prompt the subject to mark the scale as shown in Figure 6.

For each trial, the glare source was exposed for three 2 second exposures, separated by 2 seconds. The subjects then marked their response on the visual analog scale. The next trial commenced after they had recorded their response and had resumed fixating on the monitor. The experimental run finished when all 36 trials had been completed. Each experimental run lasted approximately nine minutes for the subjective method.

Objective Method

Discomfort glare was assessed using the objective technique under identical conditions. For each of the 36 trials, however, the glare source was exposed for only one 2 second exposure, again controlled by the electronic shutter. Each trial was separated by a randomly varied period of between 5 and 9 seconds. EMG activity was recorded for four seconds, commencing two seconds before the shutter opened. Each experimental run lasted approximately six minutes for the objective technique.

RESULTS AND ANALYSIS

Subjective Method

For the subjective measures of discomfort, the subjects' marks on the VAS scale were identified to the nearest millimeter with values ranging from 0 to 100. Values were averaged across trials and plotted as a function of glare source luminance for each experiment condition. Data from a typical subject are shown in Figure 7. For a given condition, increasing source luminance produced a monotonic increase in discomfort rating. The reduced ambient illumination consistently produced higher discomfort ratings while the reduced source diameter resulted in lower values. In order to allow quantitative comparisons between conditions, across subjects, and with objective findings we determined the log luminance of the glare source, termed VAS_{50}, corresponding to a discomfort rating of 50, by linear interpolation. This value represents the luminance to achieve the border between "annoying" and "disturbing discomfort". The mean VAS_{50} values for each condition are given in Table 1.

Objective Method

The objective EMG data were analyzed on a trial by trial basis. The four second sample of EMG activity was divided into two equal parts: the first reflecting the absence of the glare source, and the second reflecting the presence of the glare source. Each 2 second EMG sample was subjected to Fourier analysis which determined the relative amount of power at each frequency. Frequencies below 10 Hz and at 60 Hz and its harmonics were removed to eliminate blink and power line artifacts. The Fast Fourier Transfer (FFT) power spectrum was then integrated (by determining the area under the power spectrum) in order to provide an index of EMG activity. An example of the FFT spectrum, with and without the glare source is shown in Figure 8. The relationship between these two integrals (before and during glare exposure) was used as an index of discomfort. We calculated an Objective Discomfort Ratio (ODR) by applying the following formula:

$$\mathbf{ODR} = \frac{\text{Integrated EMG power spectrum with glare source}}{\text{Integrated EMG power spectrum without glare source)}} - \mathbf{1}$$

A value of zero for the ODR reflects no change in EMG activity, while a value of one represents a doubling of activity.

Objective discomfort ratios were averaged across trials and plotted as a function of glare source luminance for each experimental condition. Data from a typical subject are shown in Figure 9. Following the trends seen with the subjective technique, reduced ambient illumination tends to produce a more sensitive response and a higher ODRs while the reduced source diameter results in lower values. However the functions determined by the EMG response appear to have a somewhat different shape from the subjective data mainly showing little change in ODR at low glare luminances but an abrupt exponential increase in activity occurring at higher values. One subject exhibited little change in EMG activity for any of the experimental conditions. His data have been excluded from the objective analysis.

In order to facilitate quantitative analysis and comparison with the subjective data we attempted to find a continuous function which would yield a reasonably good fit to the data for each subject and experiment condition. We eventually chose the following function:

$$\mathrm{ODR} = 0.25e^{1.5*(\mathrm{LogL} - \mathrm{ODR}_{0.25})}$$

where ODR is the Objective Discomfort Ratio introduced above and logL is the log glare source luminance in cdm^{-2}). The exponent multiplier of 1.5 was adopted since it gave a reasonable fit to most subjects' data. The quantity $ODR_{0.25}$ is the log glare source luminance at which the Objective Discomfort Ratio is equal to 0.25, equivalent to a 25% increase in EMG activity. The mean $ODR_{0.25}$ values averaged over 19 subjects for each condition are given in Table I.

Comparison of Objective and Subjective Methods

For virtually all subjects, there appeared to be good qualitative agreement between the objective and the subjective results (see Figs. 7 and 9). Furthermore, the mean subjective (VAS_{50}) and objective ($ODR_{0.25}$) values show good agreement for all conditions. The objective $ODR_{0.25}$ and subject VAS_{50} values for each subject and each condition are plotted for each condition in Figure 10. It can be seen that, while, the three conditions form clusters, there is substantial between-subject variation. This raises the question of how well the objective method correlates with the subjective method.

In order to address this issue we performed a second analysis making use of within-subject comparisons. We used the glare luminances that yielded the criterion values of VAS_{50} and $ODR_{0.25}$ from the moderate room illumination/2 deg. aperture condition (condition 1) to form a baseline and calculated the change in log glare source luminance necessary to produce the same criterion discomfort level (VAS_{50} and $ODR_{0.25}$) for the other conditions. It should be expected that a reduction in room illumination (condition 2 - condition 1) should produce lower VAS_{50} and $ODR_{0.25}$ values. Conversely a reduction in the size of the glare source (condition 3 - condition 1) should produce higher VAS_{50} and $ODR_{0.25}$ values. These values are plotted in Figures 11 and 12. Subjects have been ranked based on their subjective VAS_{50} value for the moderate illumination/2 deg. source condition.

For the subjective method, lowering the room illumination produced the anticipated lower VAS_{50} values in all 20 subjects (see Fig. 11). Conversely, reducing the size of the glare source produced the expected higher VAS_{50} values in 16 of 20 subjects. For the objective method, lowering the room illumination produced the anticipated lower $ODR_{0.25}$ values in 15 of 19 subjects (see Fig. 12). Conversely, reducing the size of the glare source produced the expected higher $ODR_{0.25}$ values in 15 of 19 subjects. Significant between-subject variation is evident for both techniques.

DISCUSSION

As displayed in Figure 10, the between-subject variation in responses are similar to those reported in previous studies[24,25]. For most conditions the glare luminances required to achieve the subjective VAS_{50} response for individual subjects spanned a two log unit range. The glare luminances required to reach the objective ODR criterion generally exhibited a narrower range. This may indicate that the between-subject variations found in the subjective assessment of discomfort glare are in part due to individual criterion differences, that do not contribute to the EMG response. Alternatively, the lower range of values observed for the objective EMG method may be a product of our curve fitting procedures.

The large between-subject variation in subjective estimates of discomfort make us wary of adopting the subjective VAS_{50} values as a gold standard against which the objective EMG technique should be evaluated. For this reason we performed the within-subject analysis detailed in the results section. We feel that this gives a much truer indication of the validity of the subjective and objective techniques without any a priori assumption that the values from one technique are superior. This analysis indicates that both techniques are sufficiently sensitive to demonstrate reliable changes in discomfort due to modest changes in glare source size or background illumination.

With the objective EMG technique, and the within subject comparison, the changes occurring in the $ODR_{0.25}$ value (the glare source luminance required to increase EMG activity by 25%) are in the expected direction for 79% of comparisons (see Fig. 12). This compares respectably with the subjective data where changes is the VAS_{50} value are in the anticipated direction for 90% of comparisons. Furthermore, the magnitude of the differences between the mean values of $ODR_{0.25}$ for each condition are very similar to differences in the subjective VAS_{50} values (see Table I).

The change in both the objective $ODR_{0.25}$ and subjective VAS_{50} values produced by altering the experimental conditions (see Table I) are in the direction predicted by accepted discomfort glare theory. Furthermore, the magnitude of these objective and subjective differences are similar to those determined by Bennett (19XXX)

The mean values shown in Table I demonstrate that the glare luminance required to produce a 25% increase in EMG activity ($ODR_{0.25}$) is higher than that corresponding to the subjective measure of disturbing comfort (VAS_{50}). The decision to reference all objective results to an ODR equal to 25% was made somewhat arbitrarily and it seems appropriate to calculate the exact ODR corresponding to the subjective rating of disturbing discomfort. We found that an ODR of 0.18 corresponded most closely to the subjective rating of disturbing discomfort. It should be noted that adopting this modified value for the ODR of 0.18 does not influence the analysis displayed in Figure 12.

We plan to our extend our investigations in a number of directions. First, we are investigating discomfort glare for larger sources to simulate light fixtures and windows using both subjective and objective measures. In addition, we are assessing the influence of the spectral composition of the glare source on discomfort. Finally, we are developing a portable device for use by lighting engineers capable of facilitating objective assessment of discomfort glare in the field.

As mentioned earlier, the EMG activity measured here is presumed to be an incipient response; manifested in the increased electrical activity of the orbicularis oculi. It is unlikely that this facial muscle or any other facial muscle is the source of the discomfort, i.e., the particular pain fibers where the discomfort initiates. The electrical activity measured in response to the pain sensation whose specific origin is yet to be determined. Nevertheless, we have shown that an objective measure of response to discomfort glare can be obtained which correlates well with subjective perceptions. Furthermore, we expect that EMG techniques will lead to useful tools for enhancing the ability of practitioners to evaluate lighting environments.

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FIGURE CAPTIONS

Figure 1. The influence of a glare source on the EMG. A four second sample of the raw EMG (in microvolts) is shown. An uncomfortable glare source is introduced after two seconds which produces a clear increase in EMG amplitude.

Figure 2. The influence of a blink on the EMG. The blink causes a large, slow change in potential lasting some 250 msec. The appearance is very different from the effect of a glare source. The influence of the blink on the FFT spectrum is shown in Fig. 3.

Figure 3. The influence of a blink on the EMG as reflected in the FFT power spectrum. The "blink" spectrum is derived from the first second of EMG activity shown in Fig. 2. The "no blink" spectrum is derived from the last second of the trace. Notice that most of the difference occurs at 10 Hz and below.

Figure 4. A subject wired for EMG recording. Two electrodes are placed just above the brow while a third serves as a ground. For this recording, electrodes are placed at both the orbicularis oculi and the corrugator supercilii. (LBL XBC-910-8313)

Figure 5. Experimental apparatus. The subject fixates a monitor on which a large symbol is displayed. The glare source is provided by a projector lamp with its beam positioned 11 degrees to the right of fixation and directed at the subject. Exposure to the source was controlled by an electronic shutter placed in front of the projector lens. Subjects record their subjective responses on a Visual Analog Scale.

Figure 6. Visual Analog Scale used in the subject assessment of discomfort glare. The check mark corresponds to a glare source which is annoying but does not approach disturbing. See appendix for full description of the scale.

Figure 7. Subjective VAS ratings for subject BH plotted as a function of glare source luminance for each experiment condition. The dashed line corresponds to VAS_{50}, the glare luminance necessary to just produce "disturbing discomfort".

Figure 8. The influence of the glare source on a FFT power spectrum. The "baseline" FFT power spectrum is derived from the first two seconds of the EMG trace shown in Fig. 1. The "glare" FFT power spectrum is derived from the last two seconds of the EMG trace. The introduction of the glare source produces a marked increase in power at all temporal frequencies above 10 Hz. Note that power line artifacts have been removed by digitally filtering frequencies at 60 Hz at its harmonics.

Figure 9. Objective Discomfort Ratios (ODR) for subject BH as a function of glare source luminance for each experimental condition. The dashed line corresponds to $ODR_{0.25}$, the glare luminance necessary to produce a 25% increase in EMG activity.

Figure 10. $ODR_{0.25}$ values as a function of VAS_{50} (both in log cdm^{-2}) for each subject and experimental condition.

Figure 11. Change in subjective VAS_{50} values produced by a reduction in ambient illumination and a reduction in the size of the glare source. Data are shown for all 20 subjects, ranked based on the glare luminance to achieve their subjective VAS_{50} value under the moderate illumination/2 deg. condition.

Figure 12. Change in objective $ODR_{0.25}$ values produced by a reduction in ambient illumination and a reduction in the size of the glare source. Data are shown for 19 subjects, ranked based on the glare luminance to achieve their subjective VAS_{50} value under the moderate illumination/2 deg. condition.

Table I. Mean (± standard deviation) luminance values corresponding to a subjective rating of 50 on the VAS scale (VAS_{50}) and a 25% increase in the objective EMG ($ODR_{0.25}$). All values are in log cdm^{-2}.

	Low Illumination 2 deg. source	Moderate Illumination 2 deg. source	Moderate Illumination 1 deg. source
Subjective VAS_{50}	5.58 ± 0.57	6.02 ± 0.48	6.26 ± 0.58
Objective $ODR_{0.25}$	5.82 ± 0.37	6.17 ± 0.49	6.50 ± 0.42

APPENDIX

Instructions to Subjects

We will require you to rate the glare source using the scale provided. The scale consists of these four levels:

Perceptible

The point at which you would prefer the light not to be present. Imagine that it is a pilot light on a computer and you are obliged to set the pilot light on/pilot light off. This is the level at which you would begin to care about such a decision.

Annoying

You could live with this glare source present if you were borrowing someone else's computer for a day. If this glare source were present, you would prefer to remove the glare source if it were possible, but could live with this annoyance for the next hour or so.

Disturbing

This makes you feel uncomfortable. If you had to work like this for any reasonable length of time, (5 minutes or so), you would do something to cover the source, shield my eyes, etc., in order to avoid the discomfort.

Intolerable

You could not imagine yourself working with the light source like this. You would certainly close your eyes or take another avoidance action.

Fig. 1 The influence of a glare source on the EMG. A four second sample of the raw EMG (in microvolts) in shown. An uncomfortable glare source is introduced after two seconds which produces a clear increase in EMG amplitude.

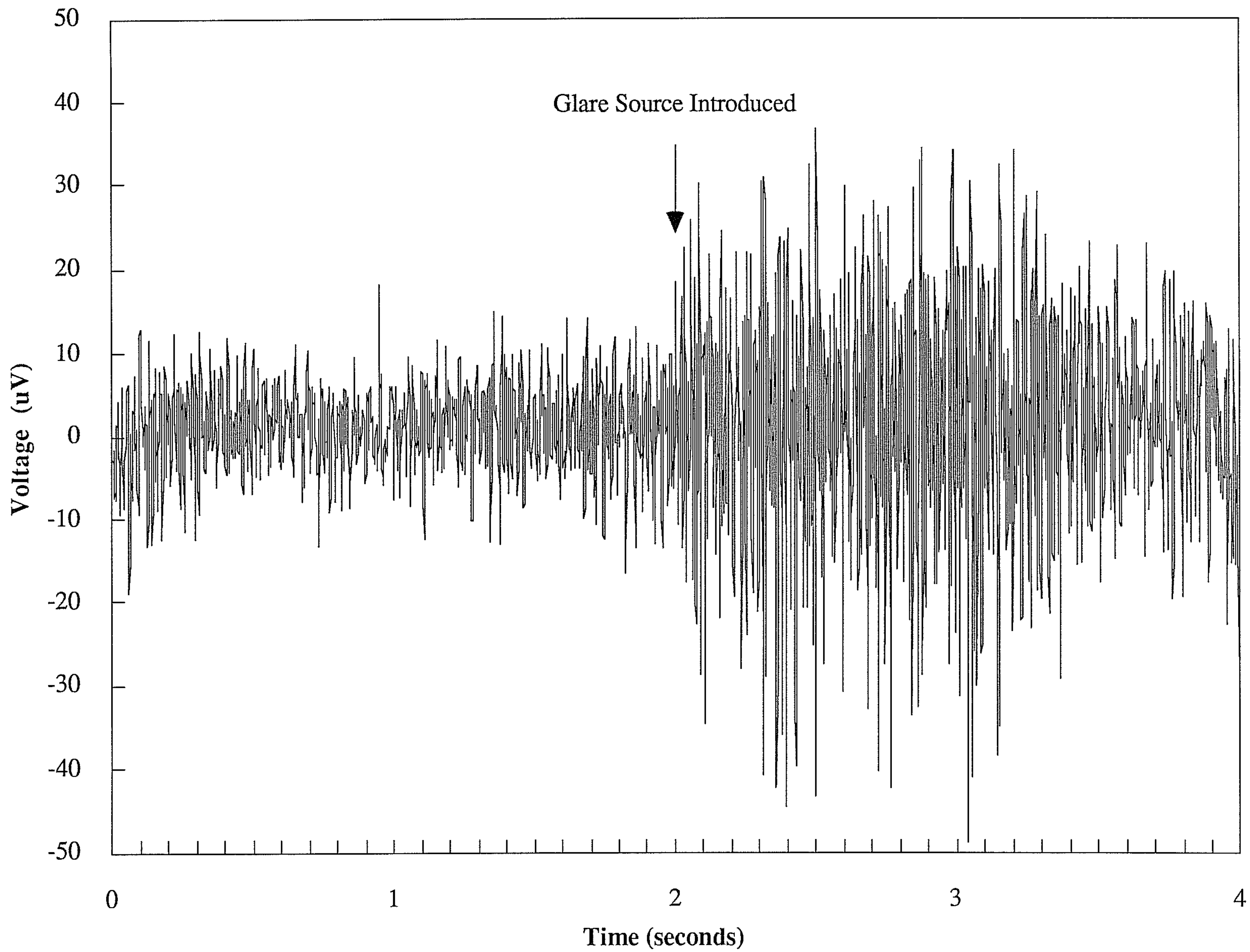

Fig. 2. The influence of a blink on the EMG. The blink causes a large, slow change in potential lasting some 250 msec. The appearance is very different from the effect of a glare source. The influence of the blink on the FFT spectrum is shown in the Figure 3.

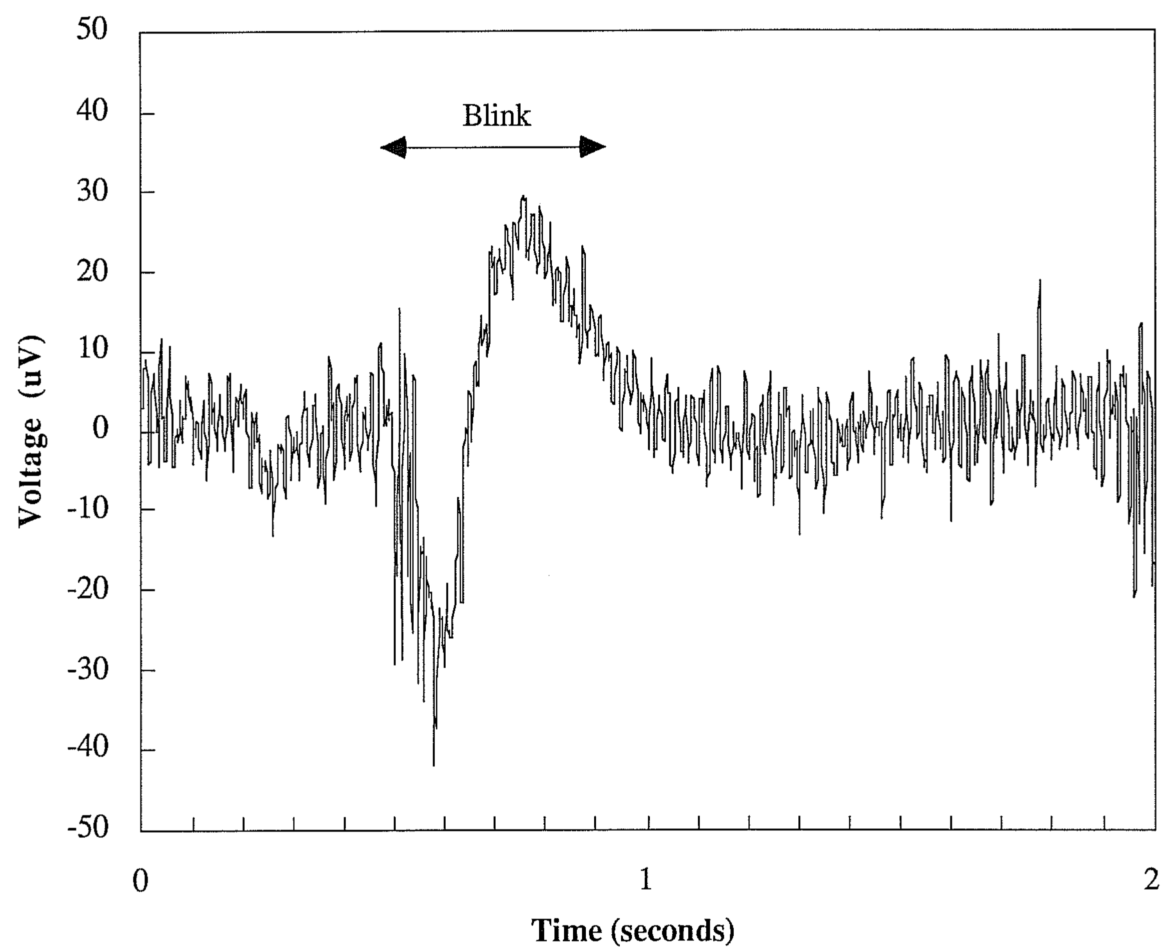

Fig. 3. The influence of a blink on the EMG as reflected in the FFT power spectrum. The "blink" spectrum is derived from the first second of EMG activity shown in Fig. 2. The "no blink" spectrum is derived from the last second of the trace. Notice that most of the difference occurs at 10 Hz and below.

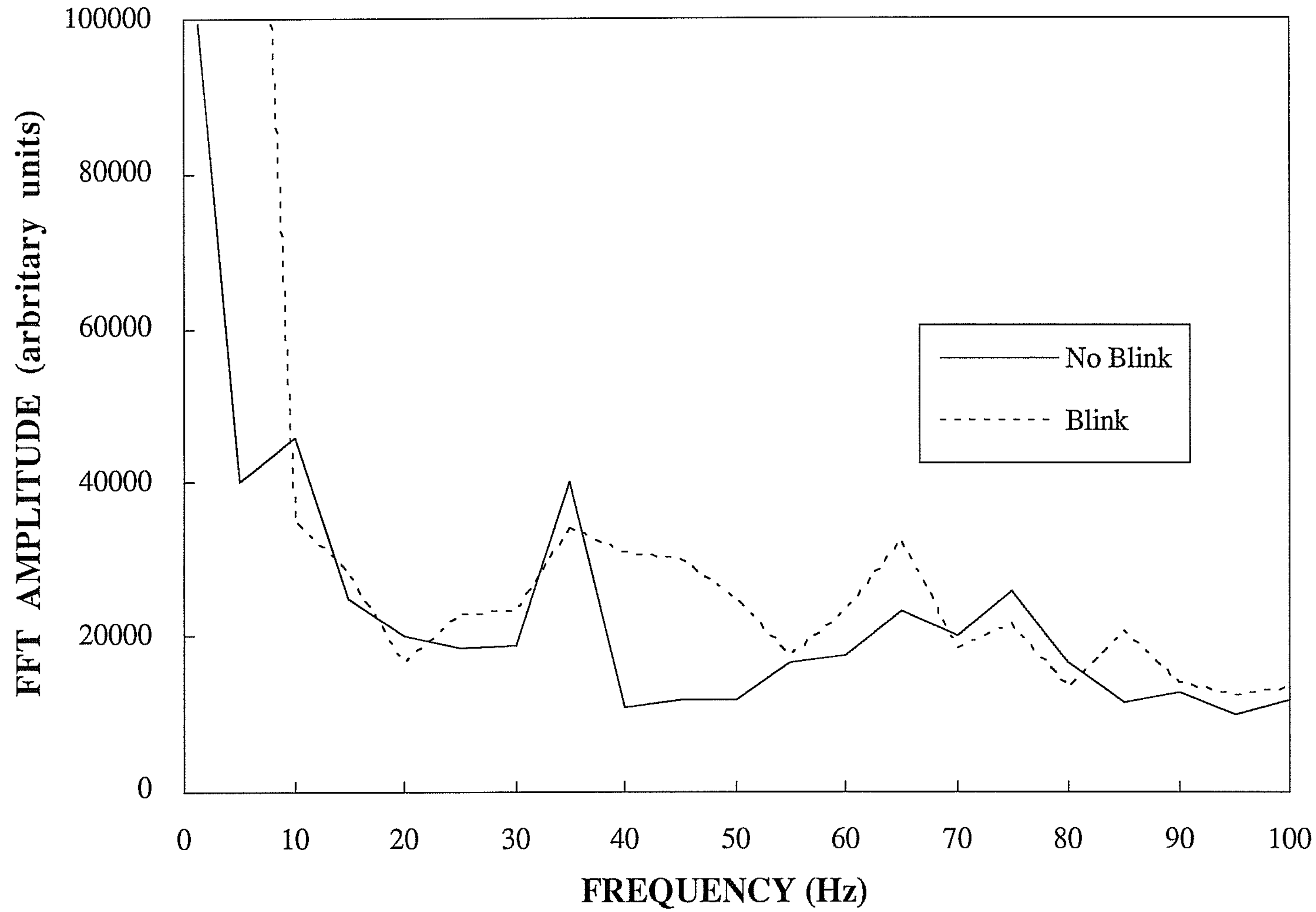

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FIGURE 4. A SUBJECT WIRED FOR EMG RECORDING. TWO ELECTRODES ARE PLACED JUST ABOVE THE BROW WHILE A THIRD SERVES AS A GROUND.

Fig. 5. Experimental apparatus. The subject fixates a monitor on which a large symbol is displayed. The glare source is provided by a projector lamp with its beam positioned 11 degrees to the right of fixation and directed at the subject. Exposure to the source was controlled by a electronic shutter placed in front of the projector lens. Subjects record their subjective responses on a Visual Analog Scale.

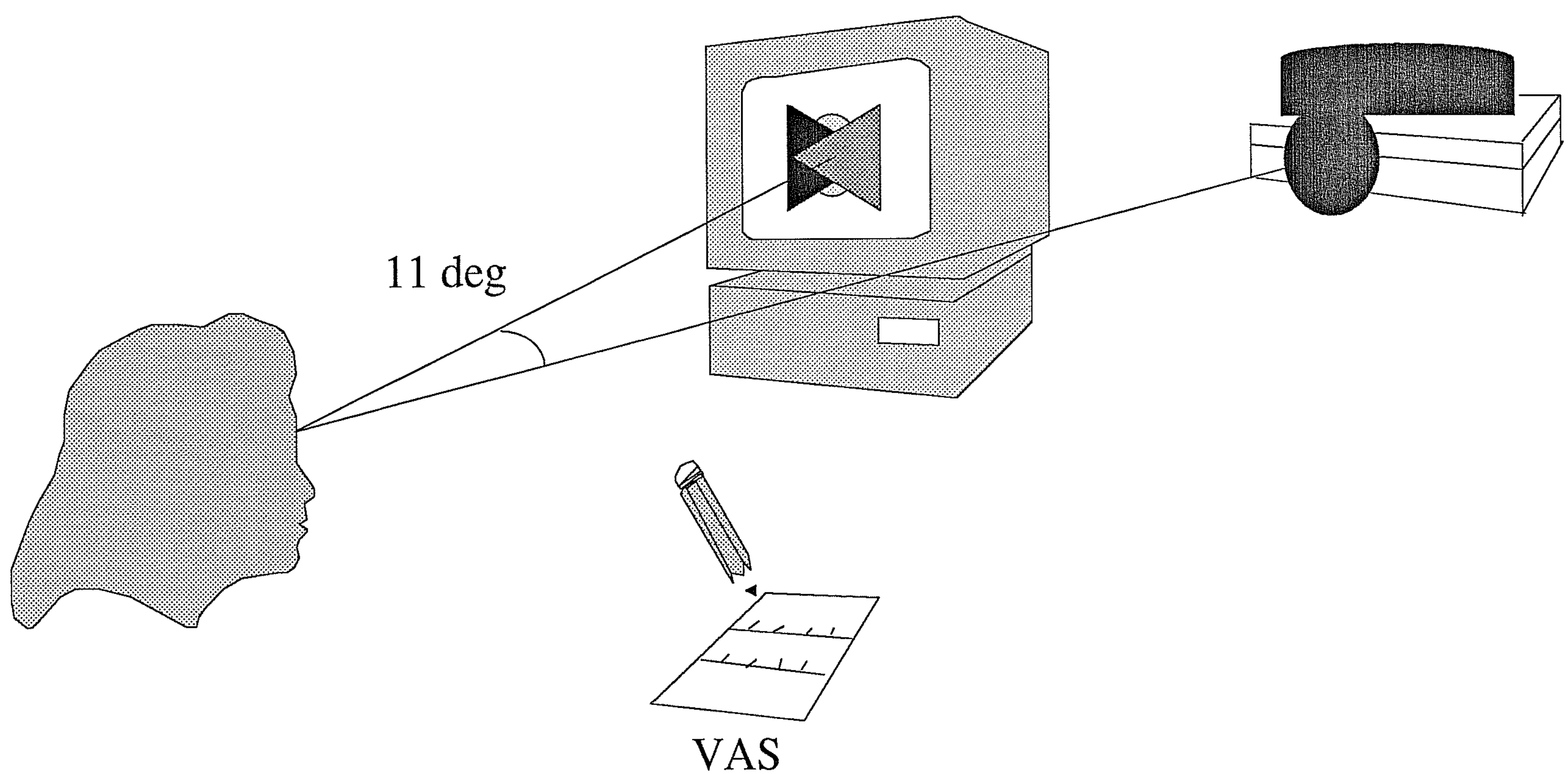


Fig. 6. Visual Analog Scale used in the subject assessment of discomfort glare. The check mark corresponds to a glare source which is annoying but does not approach disturbing. See appendix for full description of the scale.

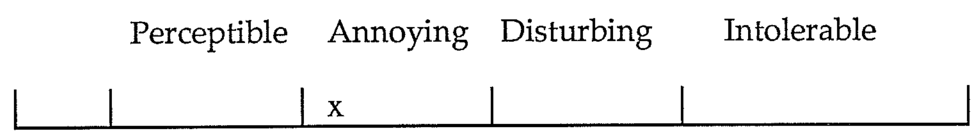


Fig. 7. Subjective VAS ratings for subject BH plotted as a function of glare source luminance for each experiment condition. The dashed line corresponds to VAS_{50}, the glare luminance necessary to just produce "disturbing discomfort".

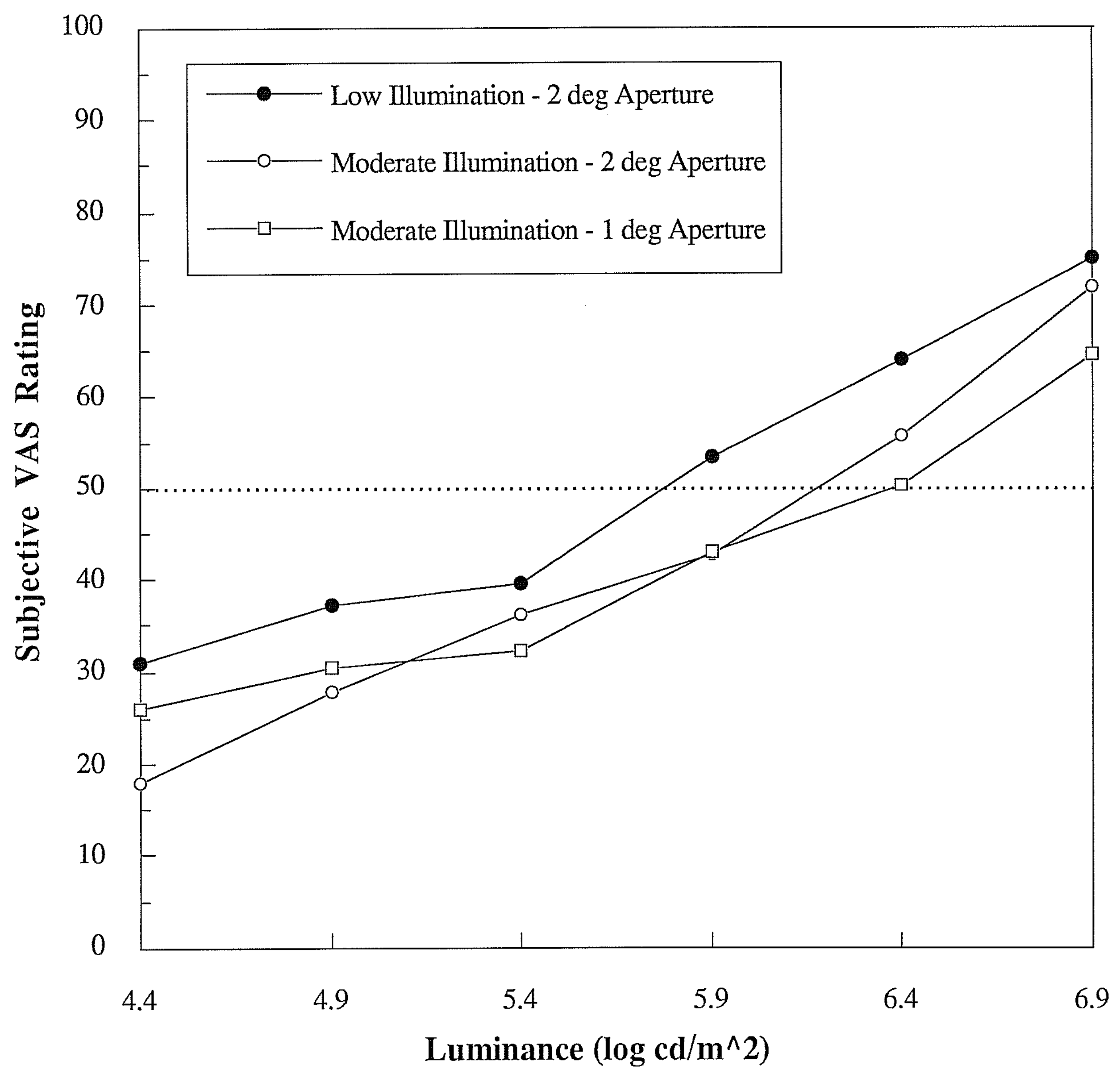


Fig. 8. The influence of a the glare source on the FFT power spectrum. The "baseline" FFT power spectrum is derived from the first two seconds of the EMG trace shown in Fig. 1. The "glare" FFT power spectrum is derived from the last two seconds of the EMG trace. The introduction of the glare source produces a marked increase in power at all temporal frequencies above 10 Hz. Note that power line artifacts have been removed by digitally filtering frequencies at 60 Hz at its harmonics.

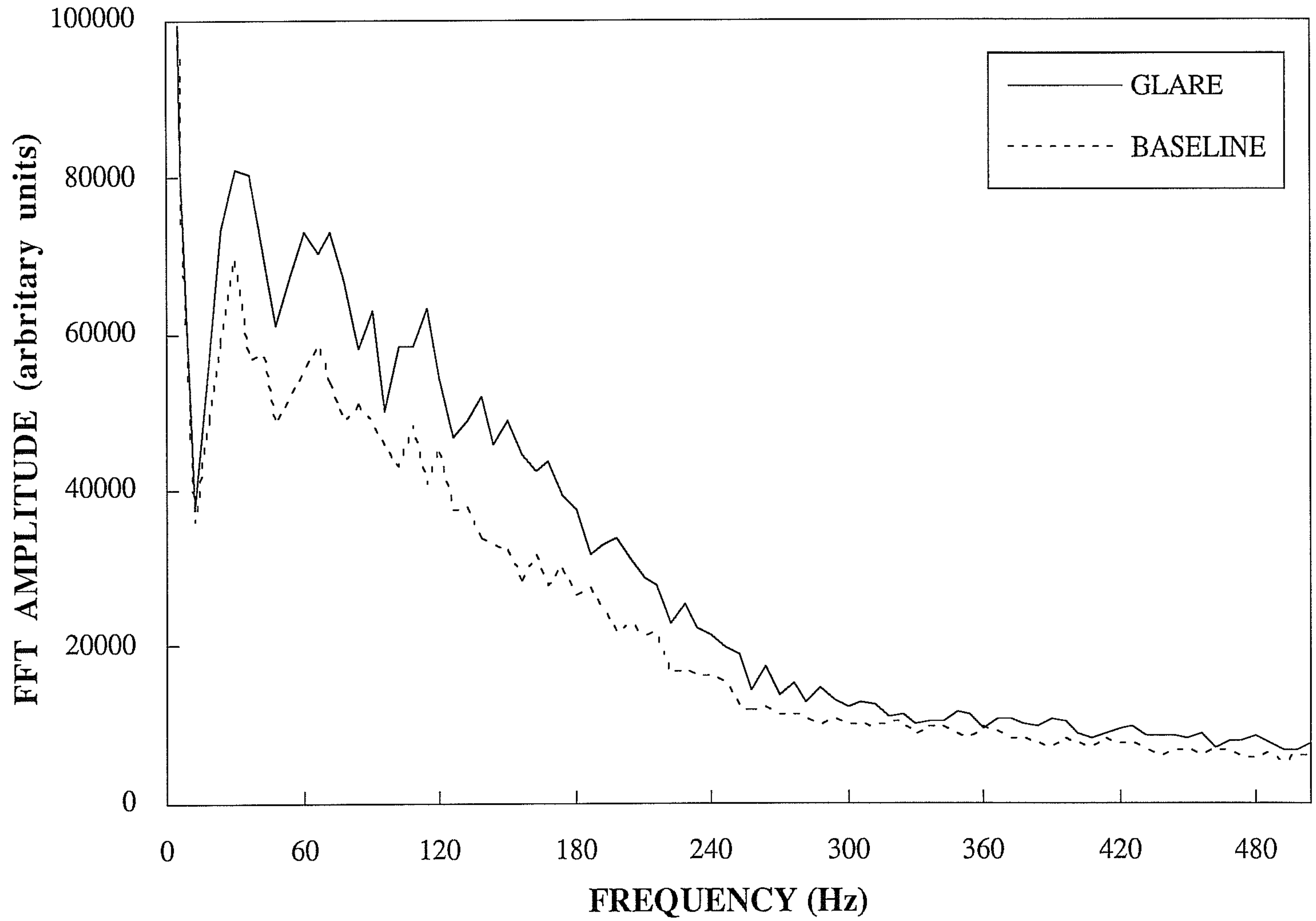


Fig. 9. Objective Discomfort Ratios (ODR) for subject BH as a function of glare source luminance for each experimental condition. The dashed line corresponds to $ODR_{0.25}$, the glare luminance necessary to produce a 25% increase in EMG activity.

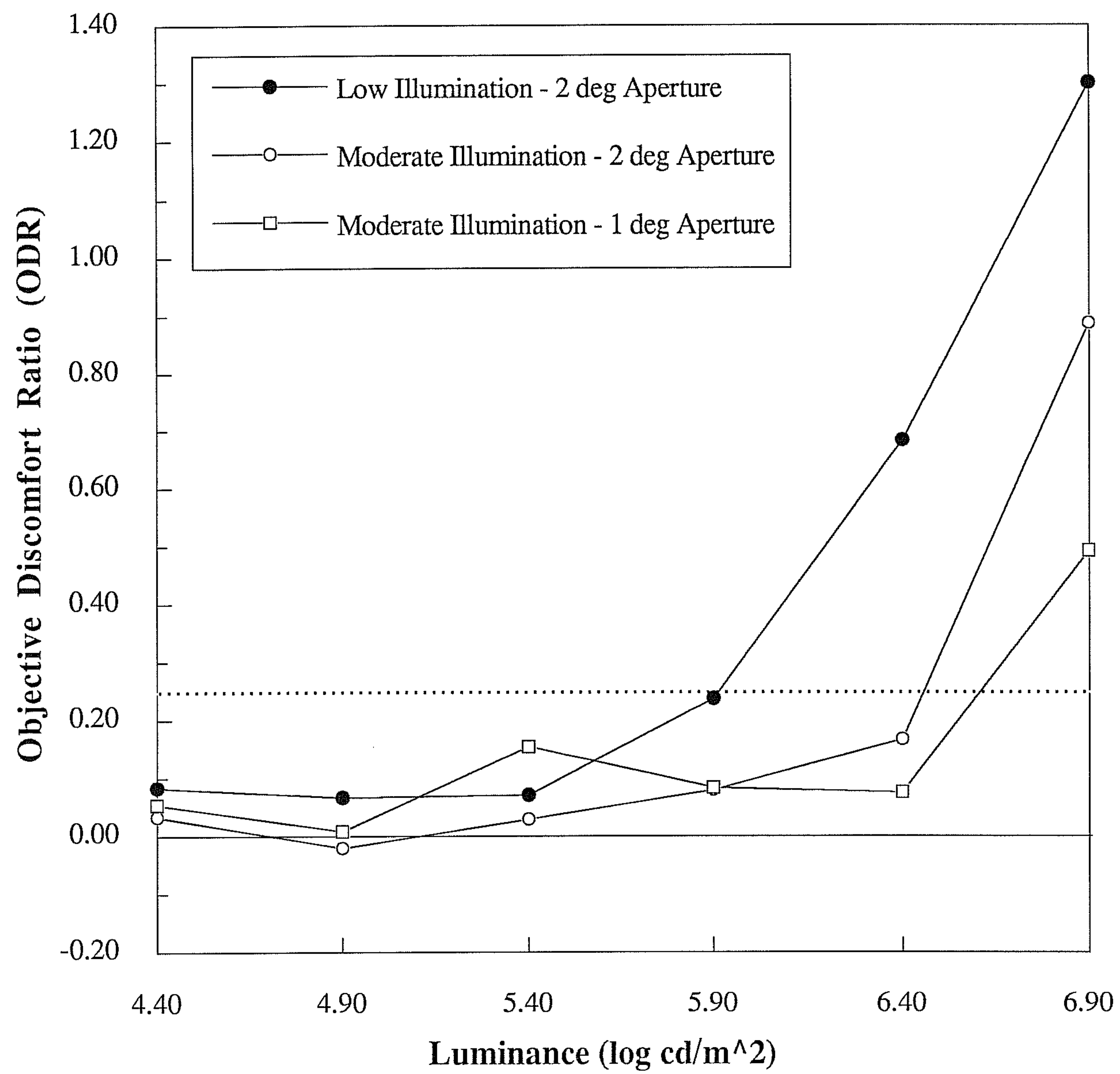


Fig. 10. $ODR_{0.25}$ values as a function of VAS_{50} (both in log cdm^{-2}) for each subject and experimental condition.

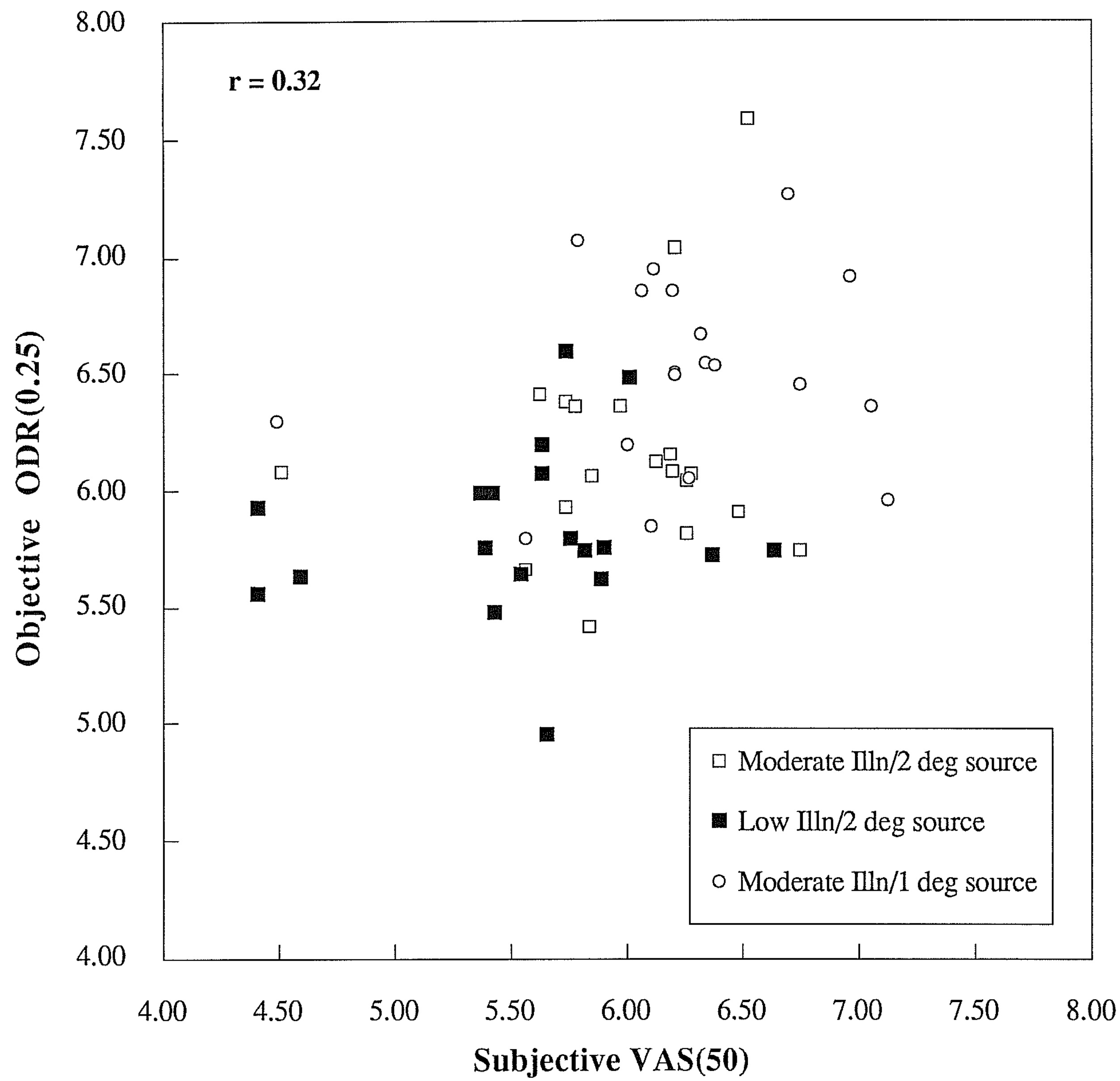


Fig. 11. Change in subjective VAS_{50} values produced by a reduction in ambient illumination and a reduction in the size of the glare source. Data are shown for all 20 subjects, ranked based on the glare luminance to achieve their subjective VAS_{50} value under the moderate illumination/2 deg condition.

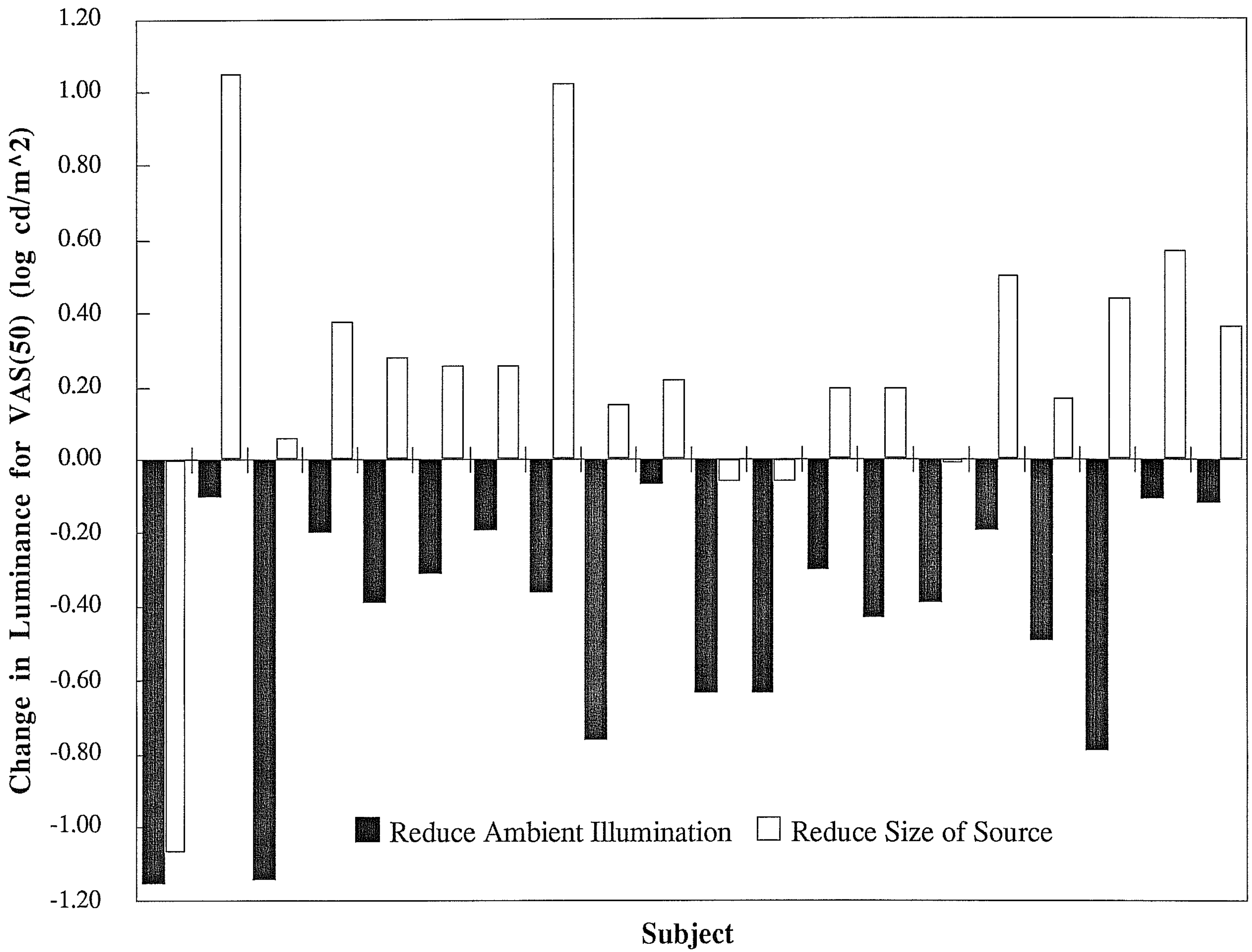
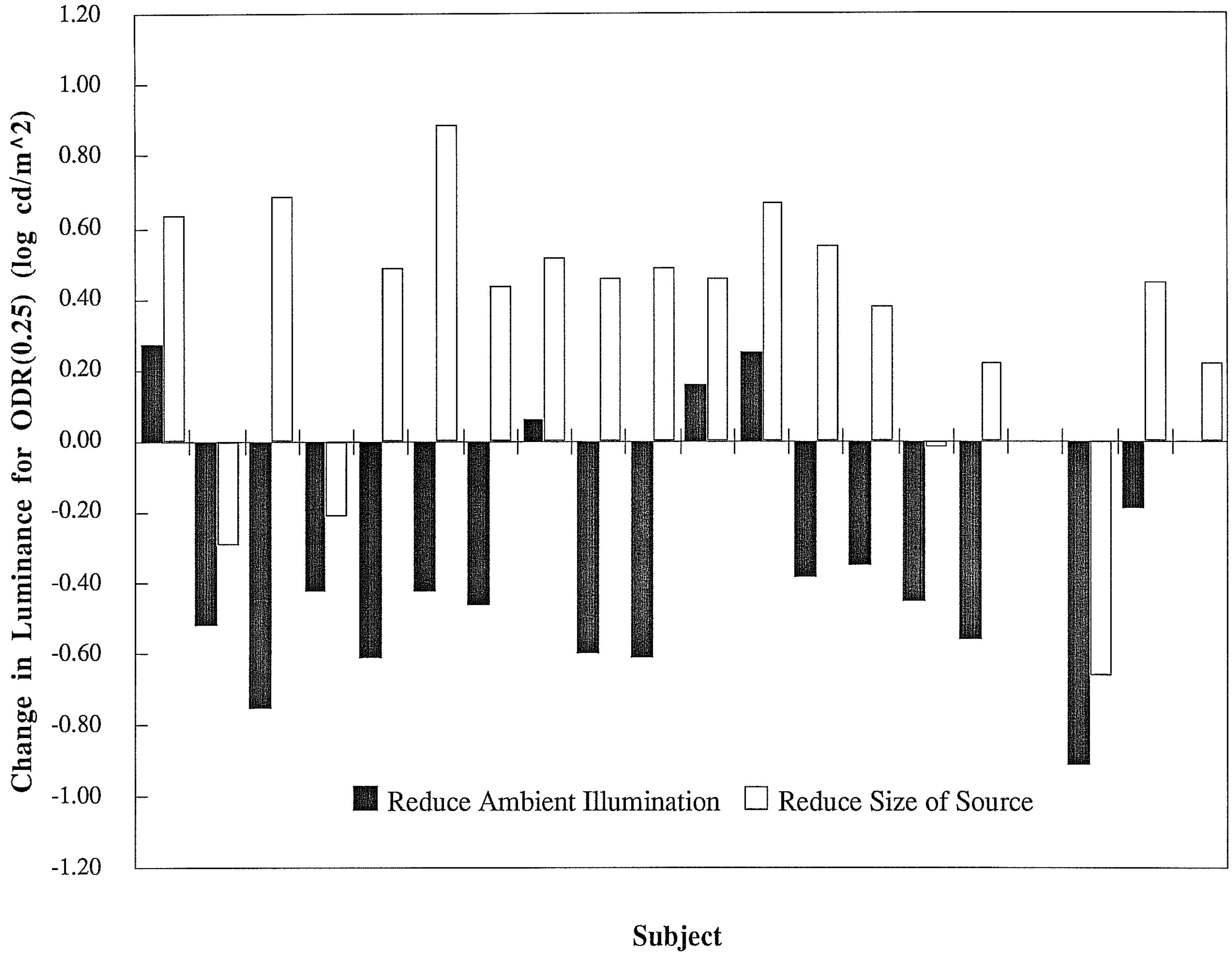


Fig. 12. Change in objective $ODR_{0.25}$ values produced by a reduction in ambient illumination and a reduction in the size of the glare source. Data are shown for 19 subjects, ranked based on the glare luminance to achieve their subjective VAS_{50} value under the moderate illumination/2 deg condition.



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Intolerable

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Discussion:

There has long been a need to find some objective measure of discomfort glare which could be validated against a subjective measure. The authors suggest that the EMG associated with certain facial muscles might be the objective method of choice. I applaud the authors for their work in this direction. However, I do have a couple of comments/questions regarding the research.

(1) The electrical activity of facial muscles may actually have little to do with the actual mechanisms of discomfort glare, and the authors do suggest this possibility. One wonders if this measure just reflects discomfort in general. What would the response be to the presentation of white noise of different intensities and durations? The finding that the ear lobe also gave equivalent results to the locations used in the study is suggestive of some sort of generalized response to annoyance.

(2) Are the authors going to utilize the concepts of VCP and DGR in their future research? It could lend more credence to their findings.

(3) Have the response times to the glare stimulus onset of this objective measure been examined? If so, what were the findings?

(4) Finally, their results shown in Figs. 7 and 9 would seem to indicate that as source luminance increases, there is a greater increase for the 2 degree target against the low luminance background vs. the medium luminance background and least for the 1 degree medium luminance background. The same results appear to hold for both subjective and objective measures. However, the explanation used to address between-subject differences appears to suggest the opposite. The description of these results seems a bit confusing.

Discussant: E.J. Rinalducci

Response to E.J. Rinalducci

1. Dr. Rinalducci is correct to point out that the EMG "may actually have little to do with the actual mechanisms of discomfort glare". We have stated in the introduction that it is an "efferent pathway response to a discomfort glare sensation". Also as stated in the last paragraph of the paper, the observed increases in EMG signal are presumed to be a measure of incipient response resulting in increased muscular electrical activity. The response could indeed reflect discomfort in general. We again acknowledge this possibility and have described our experiences using chin rests in the text. In a further experiment, in response to the discusser, we have attempted to elicit an increase in EMG activity by means of an auditory stimulus. Using a de-tuned f.m. signal, that was "uncomfortably loud", we were unable to elicit a reliable increase in EMG activity for electrodes placed on the orbicularis oculi. The earlobe was mentioned in the text as an electrical ground point not the position of the test electrodes.

2. The two ratings of discomfort glare used in lighting applications, VCP and DGR, have as their basis the subjective reporting by test subjects to various glare conditions. We believe the subjective method used here (VAS) applied to the glare indices VCP and DGR would improve their reliability. But more to the point, we are also of the opinion that these procedures have deficiencies that could be improved if instead the objective EMG was introduced as the basis measure of glare response rather than the presently used subjective measures. This alternative allows the possibility of placing the glare indices of lighting design on a much sounder footing. Perhaps the consideration of the EMG signal as the underlying basis for discomfort glare ratings will also provide the impetus to re-examine the rather arcane procedures used to define both VCP and DGR.

3. The response times have only been examined qualitatively. The onset of EMG activity occurs during the first second. Since we typically use one or two second samples of EMG activity we do not have quantitative data on response times.

4. The confusion arises from the fact that a *reduction* in the luminance that yields values of VAS_{50} and $ODR_{0.25}$ indicates that the condition is *more* uncomfortable. We have attempted to clarify our discussion of the between-subject differences by adding the arrows now appearing in Figures 11 and 12 to indicate what corresponds to increased discomfort and what constitutes decreased discomfort.